DISTANCE-ESTIMATION METHOD FOR A TRAVELING OBJECT
SUBJECTED TO DYNAMIC PATH CONSTRAINTS

The invention relates to terrain navigation in respect
5   of a mobile object subject to travel constraints
varying over time, such as an aircraft limited in terms
of rate of climb, the limit possibly being negative,
and deploying above a terrain zone exhibiting
threatening obstacles or reliefs close to or above its
10   flight altitude.

Diverse systems have been developed for forewarning the
crew of an aircraft of a risk of collision with the
ground. Some, such as the TAWS systems (the acronym
15   standing for "Terrain Awareness and Warning System"),
make a short-term trajectory forecast for the aircraft
on the basis of flight information (position, heading,
orientation and amplitude of the speed vector) provided
by the onboard equipment, situate this forecast with
20   respect to a map of the region overflown extracted from
a terrain elevation database accessible on board and
emit alarms destined for the crew of the aircraft
whenever the short-term forecastable trajectory comes
into collision with the ground. These TAWS systems
25   supplement their alarms with rudimentary
recommendations of the kind "Terrain Ahead, Pull up".
Some of them also give information about the level of
risk of collision incurred due to the reliefs and the
obstacles surrounding the aircraft in the form of a map
30   presenting the reliefs or the obstacles of the terrain
overflown as strata of different colors. However, this
map of risks of collision with the environment takes
account only of the altitudes of the relief relative to
the position of the mobile object and does not take
35   account of the existence or otherwise of a realistic
trajectory making it possible to join up with the zones
displayed.

To satisfy this requirement of ascertaining the points

of the terrain overflown that remain accessible after a maneuver for avoiding a relief or an obstacle on the ground, the map of risk of collision with the environment must display only the zones for which there is a possible route from the current position of the mobile object. The realization of such a display involves the association of a metric with a relief map derived from a terrain elevation database.

A known procedure for associating a metric with a relief map derived from a terrain elevation database with regular meshing of the terrestrial surface or of a part of the latter, consists in considering the map presenting the relief on the basis of altitude values appearing, with the geographical coordinates, latitude and longitude of the measurement points, in the elements of the terrain elevation database as an image whose pixels are the altitude values of the points of the terrain elevation database that are illustrated in the map with, as abscissa and ordinate coordinates within the image, the latitude and longitude geographical coordinates of these points appearing in the elements of the terrain elevation database and in calling upon a distance transform operating by propagation to estimate distances within this image.

Distance transforms operating by propagation also known as "chamfer distance transforms" or "chamfer Euclidean distance transforms" deduce the distance of a pixel termed the goal pixel with respect to another pixel termed the source pixel, from the distances previously estimated for the pixels of its neighborhood, through a scan of the pixels of the image. The scan makes it possible to estimate the distance of a new goal pixel with respect to the source pixel by searching for the path of minimum length going from the new goal pixel to the source pixel passing through an intermediate pixel of its neighborhood whose distance has already been estimated, the distance of the new goal pixel to an

'intermediate pixel of its neighborhood whose distance
has already been estimated being given by applying a
neighborhood mask commonly called a chamfer mask.

5   A distance transform of this kind was proposed in 1986
by Gunilla Borgefors for estimating distances between
objects in a digital image, in an article entitled:
"Distance Transformation in Digital Images" and
published in the journal "Computer Vision, Graphics and
10   Image Processing", Vol. 34 pp. 344-378. One of the
interesting benefits of these propagation-based
distance transforms is of reducing the complexity of
the calculations of a distance estimate by permitting
the use of integers.
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To select the path of minimum length giving the
distance estimate, a propagation-based distance
transform must test all the possible paths. This
obligation is manifested as a regularity constraint
20   imposed on the order of scanning of the pixels of an
image. G. Borgefors proposes, in order to satisfy this
regularity constraint, that the pixels of an image be
scanned twice consecutively, in two mutually inverse
orders, which are either lexicographic order, the image
25   being analyzed from left to right row by row and from
top to bottom, and inverse lexicographic order, or
transposed lexicographic order, the image having
undergone a 90° rotation, and inverse transposed
lexicographic order. She also proposes the adoption of
30   a chamfer mask of dimensions 3x3 with two values (3, 4)
of neighborhood distances or of dimensions 5x5 with
three values (5, 7, 11) of neighborhood distances.

Distance transforms operating by propagation are
35   already employed in the field of terrain navigation for
robots. In this context, it is known to use the
distance transform of G. Borgefors with a static
constraint consisting in routinely allocating an
infinite distance to a point under analysis when it is

apparent that it belongs to reliefs or obstacles to be circumvented that are cataloged in a memory of prohibited crossing zones, so as to eliminate, from the set of the paths tested during a distance estimation,

5 those passing through the reliefs or obstacles that the robot must circumvent. However, a distance transform operating by propagation used with a static constraint within the context of terrain navigation for robots, is not suitable for terrain navigation for aircraft for

10 which the threat presented by a relief or an obstacle on the ground depends on the vertical profile of its trajectory.

An aim of the present invention is a method of

15 estimating the distances of the points of a map extracted from a terrain elevation database with respect to a reference point employing a distance transform operating by propagation, with a dynamic constraint changing over time suitable for terrain

20 navigation for an aircraft having a trajectory with imposed vertical profile.

Its subject is a method of estimating the distances of the points of a map extracted from a terrain elevation

25 database, for a mobile object subjected to dynamic constraints prohibiting it from certain zones of the map referred to as prohibited zones of passage whose configuration varies as a function of the time of travel of the mobile object. The terrain elevation

30 database encompasses a set of points labeled by an altitude, a latitude and a longitude meshing the terrain of deployment of the mobile object. The method implements a distance transform operating by propagation over the image constituted by the elements

35 of the terrain elevation database corresponding to the map and arranged in rows and columns in orders of values of longitude and latitude. This distance transform estimates the distances of the various points of the image with respect to a source point placed in

proximity to the mobile object, by applying, by scanning, a chamfer mask to the various points of the image. The estimation of distance of a point, by application of the chamfer mask to this point termed

5 the goal point is performed by cataloging the various paths going from the goal point to the source point and passing through points of the neighborhood of the goal point which are covered by the chamfer mask and whose distances from the source point have been estimated

10 previously in the course of the same scan, by determining the lengths of the various paths cataloged by summation of the distance assigned to the point of passage of the neighborhood and of its distance from the goal point, extracted from the chamfer mask, by

15 searching for the shortest path among the paths cataloged and by adopting its length as estimate of the distance of the goal point. Initially, at the start of the scan, a distance value greater than the largest distance measurable on the image allocated to all the

20 points of the image except for the source point, origin of the distance measurements, to which is assigned a zero distance value. The method is noteworthy in that the lengths of the paths cataloged, during the application of the chamfer mask to a goal point, with a

25 view to searching for the shortest path, are translated into times of travel for the mobile object and in that the cataloged paths whose times of travel for the mobile object are such that the goal point would belong to a prohibited zone of passage at the moment at which

30 the mobile object reached it, are excluded from the search for the shortest path.

Advantageously, when the mobile object is an aircraft having a vertical flight profile to be complied with

35 determining the evolution of its instantaneous altitude, there are associated, with the lengths of the cataloged paths, the forecastable values of the instantaneous altitudes that the aircraft would have by reaching the goal point via these paths while complying

with the vertical flight profile imposed, and the cataloged paths associated with forecastable values of altitude that are less than or equal to the goal point altitude given by the terrain elevation database and
5   increased by a protection margin are eliminated from the search for the shortest path.

Advantageously, when the mobile object is an aircraft having an imposed vertical flight profile, the distance
10   estimation operated by propagation over the image constituted from the elements of the terrain elevation database corresponding to the map is doubled up with an estimation of the forecastable altitude of the aircraft in line with the various points of the image by
15   assuming that it follows the shortest path selected for the distance estimation and that it complies with the vertical flight profile imposed.

Advantageously, when the mobile object is an aircraft
20   with imposed vertical flight profile and when the distance estimate is doubled up with an estimate of the forecastable altitude of the aircraft, the altitudes of the various points of the map are subtracted from the estimates of the forecastable altitudes of the aircraft
25   at these points to obtain deviations with respect to the ground.

Advantageously, when the mobile object is an aircraft with imposed vertical flight profile and when the
30   distance estimate is doubled up with an estimate of the forecastable altitude of the aircraft, the altitudes of the various points of the map are subtracted from the estimates of the forecastable altitudes of the aircraft at these points to obtain deviations with respect to
35   the ground displayed on the map as color strata.

Advantageously, the propagation-based distance transform scans the pixels of the image constituted from the elements of the terrain elevation database

' corresponding to the map, in several successive passes according to different orders.

Advantageously, the propagation-based distance transform scans the pixels of the image constituted from the elements of the terrain elevation database belonging to the map, in several successive passes according to different orders and repeatedly until the distance estimates obtained stabilize.

Advantageously, the propagation-based distance transform scans the pixels of the image constituted from the elements of the terrain elevation database corresponding to the map, in several successive passes according to different orders including lexicographic order, inverse lexicographic order, transposed lexicographic order and inverse transposed lexicographic order.

Advantageously, the propagation-based distance transform scans the pixels of the image constituted from the elements of the terrain elevation database corresponding to the map, in a series of four passes that is repeated until stabilization of the distance estimates:

- a first pass performed row by row from top to bottom of the image, each row being traversed from left to right,
- a second pass performed row by row from bottom to top of the image, each row being traversed from right to left,
- a third pass performed column by column from left to right of the image, each column being traversed from top to bottom, and
- a fourth pass performed column by column from right to left of the image, each column being traversed from bottom to top.

Advantageously, the propagation-based distance

transform scans the pixels of the image constituted from the elements of the terrain elevation database corresponding to the map, in a series of eight passes that is repeated until stabilization of the distance estimates:

- a first pass performed row by row from top to bottom of the image, each row being traversed from left to right,
- a second pass performed row by row from bottom to top of the image, each row being traversed from right to left,
- a third pass performed column by column from left to right of the image, each column being traversed from top to bottom,
- a fourth pass performed column by column from right to left of the image, each column being traversed from bottom to top,
- a fifth pass performed row by row from top to bottom of the image, each row being traversed from right to left,
- a sixth pass performed row by row from bottom to top of the image, each row being traversed from left to right,
- a seventh pass performed column by column from right to left of the image, each column being traversed from top to bottom, and
- an eighth pass performed column by column from left to right of the image, each column being traversed from bottom to top.

Other characteristics and advantages of the invention will emerge from the description hereinbelow of an embodiment given by way of example. This description will be offered in conjunction with the drawing in which:

- a figure 1 represents an exemplary chamfer mask,
- figures 2a and 2b show the cells of the chamfer mask illustrated in figure 1, which are used in a scanning pass according to lexicographic order and

in a scanning pass according to inverse
lexicographic order,

- a figure 3 is a chart illustrating the main steps
of a method, in accordance with the invention, for
estimating the distance of a point having regard
to a dynamic constraint in the course of the
application of a chamfer mask,

- a figure 4 is a chart illustrating a variant of
the method of estimating the distance of a point
shown in figure 3, and

- a figure 5 is a chart of the main steps of a
method, in accordance with the invention, for
estimating, by propagation, the distances of the
set of the points of a map taking account of a
dynamic constraint and implementing a method of
estimating the distance of a point such as those
shown in figures 3 and 4.

The distance between two points of a surface is the
minimum length of all the possible routes over the
surface starting from one of the points and finishing
at the other. In an image formed of pixels distributed
according to a regular mesh of rows, columns and
diagonals, a propagation-based distance transform
estimates the distance of a pixel termed "goal" pixel
with respect to a pixel termed "source" pixel by
constructing progressively, starting from the source
pixel, the shortest possible path following the mesh of
pixels and finishing at the goal pixel, being aided by
the distances found for the image pixels already
analyzed and an array termed a chamfer mask cataloging
the values of the distances between a pixel and its
close neighbors.

As shown in figure 1, a chamfer mask takes the form of
an array with an arrangement of boxes reproducing the
pattern of a pixel surrounded by its close neighbors.
At the center of the pattern, a box assigned the value
0 labels the pixel taken as origin of the distances

‘cataloged in the array. Around this central box are clustered peripheral boxes filled with non-zero distance values and mimicking the arrangement of the pixels of the neighborhood of a pixel assumed to occupy

5   the central box. The distance value appearing in a peripheral box is that of the distance separating a pixel occupying the position of the peripheral box concerned, from a pixel occupying the position of the central box. It is noted that the distance values are

10   distributed as concentric circles. A first circle of four boxes corresponding to the four pixels closest to the pixel of the central box that are placed either on the row or on the column of the pixel of the central box are assigned a distance value D1. A second circle

15   of four boxes corresponding to the four pixels closest to the pixel of the central box that are placed outside the row and column of the pixel of the central box are assigned a distance value D2. A third circle of eight boxes corresponding to the eight pixels closest to the

20   pixel of the central box that are placed outside the row, the column and the diagonals of the pixel of the central box are assigned a value D3.

The chamfer mask can cover a neighborhood of greater or

25   lesser extent of the pixel of the central box by cataloging the values of the distances of a greater or lesser number of concentric circles of pixels of the neighborhood. It may be reduced to the first two circles formed by the pixels of the neighborhood of a

30   pixel occupying the central box or be extended beyond the first three circles formed by the pixels of the neighborhood of the pixel of the central box but it is customary to stop at first three circles like that represented in figure 1. The values of the distances

35   D1, D2, D3 which correspond to Euclidian distances are expressed in a scale permitting the use of integers at the cost of a certain approximation. Thus, G. Borgefors gives the value 5 to the distance d1 corresponding to an echelon with abscissa x or with ordinate y, the

'value 7, which is an approximation of $5\sqrt{2}$, to the distance d2 corresponding to the root of the sum of the squares of the echelons with abscissa and ordinate $\sqrt{x^2 + y^2}$, and the value 11, which is an approximation of 5 $5\sqrt{5}$, to the distance d3.

The progressive construction of the shortest possible path going to a goal pixel, starting from a source pixel and following the mesh of pixels is done by 10 regular scanning of the pixels of the image by means of the chamfer mask. Initially, the pixels of the image are assigned an infinite distance value, in fact a number high enough to exceed all the values of the distances measurable in the image, with the exception 15 of the source pixel which is assigned a zero distance value. Then the initial distance values assigned to the goal points are updated in the course of the scan of the image by the chamfer mask, an update consisting in replacing a distance value allocated to a goal point 20 with a new lesser value resulting from a distance estimate made on the occasion of a new application of the chamfer mask to the goal point considered.

An estimation of distance by application of the chamfer 25 mask to a goal pixel consists in cataloging all the paths going from this goal pixel to the source pixel and passing through a pixel of the neighborhood of the goal pixel whose distance has already been estimated in the course of the same scan, in searching from among 30 the paths cataloged, for the shortest path or paths and in adopting the length of the shortest path or paths as distance estimate. This is done by placing the goal pixel whose distance it is desired to estimate in the central box of the chamfer mask, while selecting the 35 peripheral boxes of the chamfer mask corresponding to pixels of the neighborhood whose distance has just been updated, while calculating the lengths of the shortest paths connecting the pixel to be updated to the source pixel while passing through one of the selected pixels

of the neighborhood, by addition of the distance value assigned to the pixel of the neighborhood concerned and of the distance value given by the chamfer mask, and in adopting, as distance estimate, the minimum of the path

5   length values obtained and of the old distance value assigned to the pixel undergoing analysis.

The order of scanning of the pixels of the image influences the reliability of the distance estimates

10 and of their updates since the paths taken into account depend thereon. In fact, it is subject to a regularity constraint which implies that if the pixels of the image are labeled in lexicographic order (pixels ranked in row-by-row ascending order starting from the top of

15 the image and progressing toward the bottom of the image, and from left to right within a row), and if a pixel p has been analyzed before a pixel q then a pixel p+x must be analyzed before the pixel q+x. The lexicographic order (scanning of the pixels of the

20 image row-by-row from top to bottom, and within a row, from left to right), inverse lexicographic order (scanning of the pixels of the image row-by-row from bottom to top and, within a row, from right to left), transposed lexicographic order (scanning of the pixels

25 of the image column-by-column from left to right and, within a column, from top to bottom), inverse transposed lexicographic order (scanning of the pixels by columns from right to left and within a column from bottom to top) satisfy this regularity condition and

30 more generally all scans in which the rows and columns, or the diagonals are scanned from right to left or from left to right. G. Borgefors advocates a double scan of the pixels of the image, once in lexicographic order and another time in inverse lexicographic order.

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Figure 2a shows, in the case of a scan pass in lexicographic order going from the upper left corner to the lower right corner of the image, the boxes of the chamfer mask of figure 1 that are used to catalog the

paths going from a goal pixel placed on the central box
(box indexed by 0) to the source pixel, passing through
a pixel of the neighborhood whose distance has already
formed the subject of an estimate in the course of the
5   same scan. These boxes are eight in number, arranged in
the upper left part of the chamfer mask. There are
therefore eight paths cataloged for the search for the
shortest whose length is taken as estimate of the
distance.
10

Figure 2b shows, in the case of a scan pass in inverse
lexicographic order going from the lower right corner
to the upper left corner of the image, the boxes of the
chamfer mask of figure 1 that are used to catalog the
15   paths going from a goal pixel placed on the central box
(box indexed by 0) to the source pixel, passing through
a pixel of the neighborhood whose distance has already
formed the subject of an estimate in the course of the
same scan. These boxes are complementary to those of
20   figure 2a. They are also eight in number but arranged
in the lower right part of the chamfer mask. There are
therefore eight paths cataloged for the search for the
shortest whose length is taken as estimate of the
distance.
25

The propagation-based distance transform whose
principle has just been recalled briefly was designed
originally for the analysis of the positioning of
objects in an image but it was soon applied to the
30   estimation of the distances on a relief map extracted
from a terrain elevation database with regular meshing
of the terrestrial surface. Specifically, such a map is
not furnished explicitly with a metric since it is
plotted on the basis of the altitudes of the points of
35   the mesh of the terrain elevation database of the zone
represented. In this context, the propagation-based
distance transform is applied to an image whose pixels
are the elements of the terrain elevation database
belonging to the map, that is to say, altitude values

associated with the latitude, longitude geographical
coordinates of the nodes of the mesh where they have
been measured, ranked, as on the map, by increasing or
decreasing latitude and longitude according to an array
5   with two coordinate dimensions, latitude and longitude.

For terrain navigation of mobile objects such as
robots, the propagation-based distance transform is
used to estimate the distances of the points of the
10 changing terrain map extracted from a database of
elevation of the terrain with respect to the position
of the mobile object or a close position. In this case,
it is known to take account of static constraints
consisting of map zones that the mobile object cannot
15 cross on account of their undulating configurations.
Hence, a prohibited-zone marker is associated with the
elements of the terrain elevation database appearing in
the map. It signals, when it is activated, an
uncrossable or prohibited zone and blocks any updating
20 other than initialization, of the distance estimate
made by the propagation-based distance transform in
respect of the pixel element considered.

In the case of an aircraft, the uncrossable zones
25 change as a function of the vertical profile imposed on
its trajectory so that a distance estimate under static
constraints by means of a propagation-based distance
transform is not satisfactory.

30 It is proposed that account be taken, in the definition
of the prohibited zones of passage, of the forecastable
altitude of the aircraft at each goal point whose
distance is currently being estimated. This
forecastable altitude, which quite obviously depends on
35 the path followed, is that of the aircraft after
negotiating the path adopted for the distance
measurement. The estimate of this forecastable altitude
of the aircraft at a goal point is done by propagation
in the course of the scan of the image by the chamfer

mask in a manner similar to the distance estimation. For each path cataloged going from a goal point to the source point, passing through a point of the neighborhood of the goal point, of which the distance

5 to the source point and the forecastable altitude of the aircraft have already been estimated in the course of the same scan, the forecastable altitude of the aircraft is deduced from the length of the path and the vertical profile imposed on the trajectory of the

10 aircraft. This forecastable altitude, estimated for each path cataloged going from a goal point whose distance is currently being estimated to a source point placed in proximity to the position of the aircraft, is used as a criterion for selecting the paths taken into

15 account in the distance estimation. If it is less than or equal to the altitude of the goal point appearing in the terrain elevation database plus a safety margin, the cataloged path with which it is associated is discarded and does not participate in the selection of

20 the shortest path. Once the selection of the shortest path has been made, its length is taken as distance of the goal point and the forecastable altitude of the aircraft which is associated therewith is also retained as the altitude of the aircraft at the goal point.

25

Figure 3 illustrates the main steps of the processing performed during the application of the chamfer mask to a goal point $P_{i,j}$ to estimate its distance in respect of an aircraft having an imposed vertical trajectory

30 profile. The goal point considered $P_{i,j}$ is placed in the central box of the chamfer mask. For each neighboring point P_v which enters the boxes of the chamfer mask and whose distance has already been estimated in the course of the same scan, the processing consists in:

35 - reading the estimated distance D_v of the neighboring point P_v (step 30),
- reading the altitude $A_{i,j}$ of the goal point $P_{i,j}$ in the terrain elevation database (step 31),
- reading the coefficient C_{XY} of the chamfer mask

corresponding to the box occupied by the neighboring point P_V (step 32),

- calculating the propagated distance D_P corresponding to the sum of the estimated distance D_V of the neighboring point P_V and of the coefficient C_{XY} assigned to the chamfer mask box occupied by the neighboring point P_V:

$$D_P = D_V + C_{XY}$$

(step 33),

- calculating the forecastable altitude A_P of the aircraft after crossing of the distance D_P directly from the distance D_P if the vertical profile imposed on the trajectory of the aircraft is defined as a function of the distance traveled $PV(D_P)$ and takes implicitly into account the time of travel or indirectly by way of the time of travel if the vertical profile imposed on the trajectory of the aircraft is defined by a rate of change of altitude (step 34),

- comparing the forecastable altitude A_P obtained with that $A_{i,j}$ of the goal point $P_{i,j}$ as derived from the terrain elevation database increased by a safety margin Δ (step 35),

- eliminating the propagated distance D_P if the forecastable altitude A_P is less than or equal to that $A_{i,j}$ of the goal point $P_{i,j}$ as derived from the terrain elevation database and augmented by the safety margin Δ (step 36),

- if the forecastable altitude A_P is greater than that $A_{i,j}$ of the goal point $P_{i,j}$ augmented by the safety margin Δ, reading the distance $D_{i,j}$ already assigned to the goal point considered $P_{i,j}$ (step 37) and comparing it with the propagated distance D_P (step 38),

- eliminating the propagated distance D_P if it is greater than or equal to the distance $D_{i,j}$ already assigned to the goal point considered $P_{i,j}$ and

- replacing the distance $D_{i,j}$ already assigned to the goal point considered $P_{i,j}$ by the propagated

distance D_P if the latter is less (step 39).

Figure 4 illustrates the main steps of a variant of the processing performed during the application of the
5 chamfer mask to a goal point $P_{i,j}$ to estimate its distance in respect of an aircraft having an imposed vertical trajectory profile.

This variant differs in the manner of formulating the
10 forecastable altitude A_P of the aircraft. It assumes that the forecastable altitude of the aircraft at each point of the terrain elevation database calculated as a function of the vertical profile imposed on its trajectory and on the basis of the length of the path
15 selected for the distance measurement is not considered as a fleeting variable, thereby allowing the processing described in relation to figure 3, but is stored, in the same guise as the distance estimate. In this variant, steps 30, 31 of reading the estimated distance
20 D_V of the neighboring point P_V and of the altitude $A_{i,j}$ of the goal point $P_{i,j}$ in the terrain elevation database are supplemented with a step 40 of reading the forecastable altitude A_{PV} of the aircraft at the neighboring point P_V, and the calculation of the
25 forecastable altitude A_P is done (step 34') by summation of the forecastable altitude A_{PV} at the neighboring point P_V and of the variation of altitude over the distance separating the neighboring point P_V from the goal point $P_{i,j}$ due to the vertical profile
30 imposed on the trajectory of the aircraft.

The storage of the forecastable altitudes of the aircraft when the latter reaches the various points of the map which are accessible by it makes it possible to
35 establish, by subtracting therefrom the altitudes of the points of the map as derived from the terrain elevation database, a map of the maximum possibilities of overfly heights of the aircraft representing the forecastable deviations with respect to the terrain as

color strata. Such a map helps the crew of the aircraft to choose a realistic trajectory exhibiting the best ground clearance.

5   As indicated previously, the estimation of the distances of the various points of the map is done by applying a processing by chamfer mask such as those just described in relation to figures 3 and 4, to the whole set of pixels of the image formed by the elements
10   of the terrain elevation database belonging to the map, taken successively according to a regular scan comprising a minimum of two passes carried out in inverse orders.

15   Figure 5 illustrates the main steps of an exemplary global process allowing the estimation of the distances of the set of points of a relief map for a mobile object subject to dynamic constraints.

20   The first step 50 of the process is an initialization of the distances assigned to the various points of the map that are considered as the pixels of an image. This initialization of the distances consists, as indicated previously, in allocating an infinite distance value,
25   at the very least greater than the largest distance measurable on the map, for all the points of the map that are considered as goal points, with the exception of a single one considered as the source of all the distances and to which a zero distance value is
30   allocated. This source point is chosen in proximity to the instantaneous position of the mobile object on the map.

The subsequent steps 51 to 54 are passes of a regular
35   scan, in the course of which passes the chamfer mask is applied successively and repeatedly to all the points of the map that are considered as the pixels of an image, the application of the chamfer mask to a point of the map giving an estimate of the distance of this

point with respect to the source point, by execution of one of the process operations described in relation to figure 3 or figure 4.

5   The first scan pass (step 51) is done in lexicographic order, the pixels of the image being analyzed row by row from top to bottom of the image and from left to right within one and the same row. The second scan pass (step 52) is done in inverse lexicographic order, the

10   pixels of the image still being analyzed row by row but from bottom to top of the image and from right to left within a row. The third scan pass (step 53) is done in transposed lexicographic order, the pixels of the image being analyzed column by column from the left to the

15   right of the image and from top to bottom within one and the same column. The fourth scan pass (step 54) is done in inverse transposed lexicographic order, the pixels of the image being analyzed column by column but from right to left of the image and from bottom to top

20   within one and the same column.

These four passes (steps 51 to 54) are repeated as long as the distance image obtained changes. To do this, the distance image content obtained is stored (step 56)

25   after each series of four passes (steps 51 to 54) and compared with the distance image content obtained in the previous series (step 55), the loop being broken only when the comparison shows that the content of the distance image no longer varies.

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In theory, two scan passes in lexicographic order and inverse lexicographic order may suffice. However, the presence of prohibited zones of passage of concave shape may cause, in the distances propagation

35   phenomenon, dead angles enclosing pixels, for which the application of the chamfer mask does not give any distance estimate. To reduce this risk of dead angle, it is advisable to vary the direction of the distance propagation phenomenon by varying the direction of the

scan, hence the doubling of the passes with a transposition of the orders of scan corresponding to a 90° rotation of the image. For a yet better elimination of the dead angles, it is possible to undertake series of eight passes:

- a first pass performed row by row from top to bottom of the image, each row being traversed from left to right,

- a second pass performed row by row from bottom to top of the image, each row being traversed from right to left,

- a third pass performed column by column from left to right of the image, each column being traversed from top to bottom,

- a fourth pass performed column by column from right to left of the image, each column being traversed from bottom to top,

- a fifth pass performed row by row from top to bottom of the image, each row being traversed from right to left,

- a sixth pass performed row by row from bottom to top of the image, each row being traversed from left to right,

- a seventh pass performed column by column from right to left of the image, each column being traversed from top to bottom, and

- an eighth pass performed column by column from left to right of the image, each column being traversed from bottom to top.

It is possible to introduce into the series of scan passes other types of scan passes deduced from the previous passes by making the diagonals of the image play the roles previously played by the rows and columns of the image. This amounts to applying the scan passes described previously to an image rotated by 45°. In a general manner, the more the passes of a series are varied the more the risk of dead angle decreases.